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Key Points:
- Coseismic discharge and temperature decrease following two large earthquakes in Balazhang #1 hot spring are documented
- We used three different permeability models and a two end-member mixing model to constrain the mechanism of the coseismic responses
- Earthquake-induced fault zone permeability decrease that reduce the recharge of deep hot water is the mechanism

Supporting Information:
- Supporting Information S1
- Data Set S1

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Fault Zone Permeability Decrease Following Large Earthquakes in a Hydrothermal System

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Abstract Seismic wave shaking-induced permeability enhancement in the shallow crust has been widely observed. Permeability decrease, however, is seldom reported. In this study, we document coseismic discharge and temperature decrease in a hot spring following the 1996 Lijiang Mw 7.0 and the 2004 Mw 9.0 earthquakes in the Balazhang geothermal field. We use three different models to constrain the permeability change and the mechanism of coseismic discharge decrease, and we use an end-member mixing model for the coseismic temperature change. Our results show that the earthquake-induced permeability decrease in the fault zone reduced the recharge from deep hot water, which may be the mechanism that explains the coseismic discharge and temperature responses. The changes in the hot spring response reflect the dynamic changes in the hydrothermal system; in the future, the earthquake-induced permeability decrease should be considered when discussing controls on permeability.

1. Introduction

It is well known that earthquakes can cause changes in groundwater level, flow rate, temperature, and chemical composition (Manga & Wang, 2015; Rojstaczer et al., 1995; Shi & Wang, 2016; Skelton et al., 2014; Wang & Barbour, 2017) and that these changes reflect the interaction between tectonic activities and hydrological systems (Manga et al., 2012; Shi et al., 2017; Wang & Barbour, 2017). Many previous studies document that fault zone properties will change under the static and dynamic stresses produced by earthquakes (Kinoshita et al., 2015; Kitagawa et al., 2007; Shi et al., 2014; Xue, 2015), which will cause changes in subsurface transport (Wang et al., 2013). Such changes can be captured and observed through monitoring the variation in physical and chemical parameters in groundwater wells and springs (Manga & Rowland, 2009; Yan et al., 2016). Thus, monitoring the hydrological changes in fault zones provides a way to obtain the spatial and temporal changes of fault zone properties in response to earthquakes and other tectonic activities.

Because of the deterministic and straightforward relationship between earthquakes and hydrological responses, the study of coseismic responses is one of the key points in earthquake hydrology. The mechanisms proposed to explain earthquake-related hydrological responses are associated with earthquake-induced changes in aquifer parameters, especially for coseismic hydrological responses beyond the near field (Mohr et al., 2016; Shi et al., 2015; Yan et al., 2016). Most documented permeability changes in the field show permeability enhancement of different magnitudes (Elkhoury et al., 2006; Lai et al., 2016; Liao et al., 2015; Rojstaczer et al., 1995; Shi & Wang, 2014; Wang et al., 2016). Thus, hydrogeologists, geophysicists, and oil reservoir engineers tend to take permeability enhancement as an important factor in many engineering applications such as evaluating the risk of earthquakes affecting subsurface waste repositories (Carrigan et al., 1991), the safety of the water supply (Mohr et al., 2016), increasing oil well production (Beresnev & Johnson, 1994), triggering seismicity (Hill & Prejean, 2007), and geothermal exploitation (Elkhoury et al., 2006). However, laboratory experiments have shown that permeability decrease is possible under the effect of dynamic stress induced by oscillation in fluid pore pressure (Liu & Manga, 2009; Shmonov et al., 1999). Thus, it is expected that permeability decrease will also occur in the field, and the impact of earthquake-induced permeability decrease on those engineering applications should be reevaluated. In this study, we report a case of permeability decrease in a hot spring following two earthquakes in the Balazhang geothermal field, Longling, China. Such changes in the hot spring may indicate the changes in permeability over a large spatial area and thus may require that in the future more attentions is paid to the study of earthquake-induced permeability decrease.

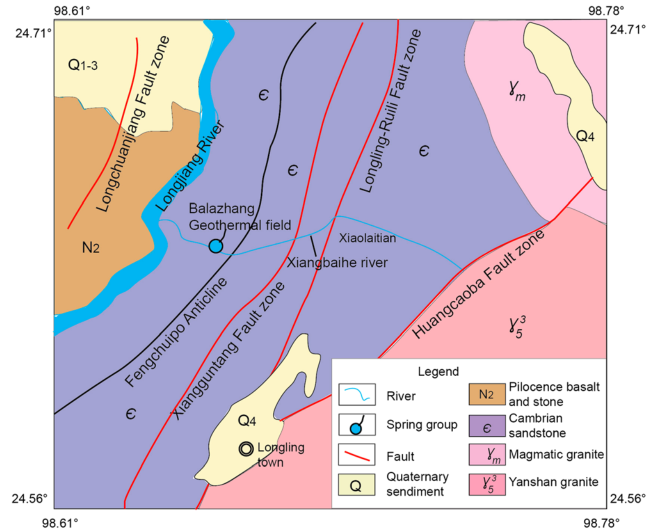

Figure 1. Geological setting of the Balazhang geothermal field.

2. Geological Setting

The hydrothermal sites distributed around Longling city form one of the important parts of the Yunnan-Tibet geothermal belt in China. Among these sites, the Balazhang geothermal field is the most famous because of its intense hydrothermal activity (Guo et al., 2017). The Balazhang geothermal field lies 12 km northwest of Longling town, where hundreds of springs with temperatures ranging from 32 °C to 97 °C are distributed on both sides of the Xiangbaihe river. Most of the springs show small discharge rates (≲0.1 L/s), and the total discharge volume of the geothermal field is approximately 15 L/s with over an area of approximately 0.2 km^2 (Xia et al., 1987). Tectonically, the Balazhang geothermal field is located near the Fengchuipo anticline, which is at the junction between the nearly east-west striking Xiangbaihe river fault and a group of northeast-southwest trending faults (Figure 1) (Xia et al., 1987). The Xiangbaihe river fault zone is considered to be the major groundwater flow path that supports the Balazhang hydrothermal field (Liu, 2009). Geophysical studies have shown that a magma pocket exists around this area, implying that the Balazhang spring may be heated by the magma pocket (Liu, 2009). The average terrestrial heat flow in this area is approximately 85 mW/m^2, which also leads to the high temperature of these springs. The springs have an average temperature of 68.1 °C, and temperatures can reach as high as the local boiling point at some springs.

3. Spring Discharge Responses

The Balazhang #1 spring is located in the Balazhang geothermal field and is collocated with an earthquake monitoring site, which began observation in 1976. Spring discharge is measured every day at 8:00 a.m. by the local staff through volumetric measurement. The spring shows steady fluctuation in the discharge, with no seasonal fluctuation (Xia et al., 1987). The water chemistry at Balazhang#1 is HCO_3-Na, with a pH of 8.12, total dissolved solids of 897.9 mg/L, F^- of 19.78 mg/L, SiO_2 of 348 mg/L, and Rn of 12,000 Bq/m^3. The hydrogen and oxygen isotope data fall close to the local meteoric water line, indicating the meteoric origin of the hot spring. We collected spring discharge data from before and after two large earthquakes: the 3 February 1996 Lijiang Mw 7.0 earthquake and the 26 December 2004 Mw 9.0 Sumatra earthquake, with epicenter distances of 331 and 2,304 km, respectively. These two large earthquakes caused significant coseismic discharge decrease that persisted for a long time. The spring discharge at Balazhang #1 decreased from 0.01085 to 0.01005 L/s after the 1996 Mw 7.0 Lijiang earthquake. Following the 2004 Sumatra earthquake, the spring discharge at Balazhang #1 decreased from 0.01057 to 0.008 L/s (Figure 2). In the following sections, we will discuss the possible mechanisms for these coseismic responses.

4. Discussion

There are two types of strain that may be responsible for the earthquake-induced changes in spring discharge: (1) earthquake-generated coseismic static strain produced by slip along the ruptured fault (Muir-Wood & King, 1993) and (2) dynamic strain caused by the passage of seismic waves leading to sustained changes in hydraulic head or aquifer permeability (Manga et al., 2016; Shi et al., 2015). The coseismic static volumetric strain caused by both the 1996 Lijiang earthquake and the 2004 Sumatra earthquake is approximately 1.02×10^{-9} and 4.08×10^{-9} as calculated by the Coulomb program (Lin & Stein, 2004; Toda et al., 2005). This scale of change in static strain is too small to change aquifer permeability and spring discharge (Manga et al., 2016; Montgomery & Manga, 2003). Thus, dynamic strain may be the dominant factor that controls the coseismic discharge.

As noticed by Manga et al. (2016) and Wang et al. (2017), three possible reasons may lead to coseismic changes in discharge under the effect of dynamic strain: (1) water released from the soil (Mohr et al., 2015), (2) liquefaction or consolidation of sediments (Manga et al., 2003), and (3) earthquake-induced permeability enhancement (Manga & Rowland, 2009; Wang et al., 2017). Since the Balazhang #1 spring occurs in hard rock

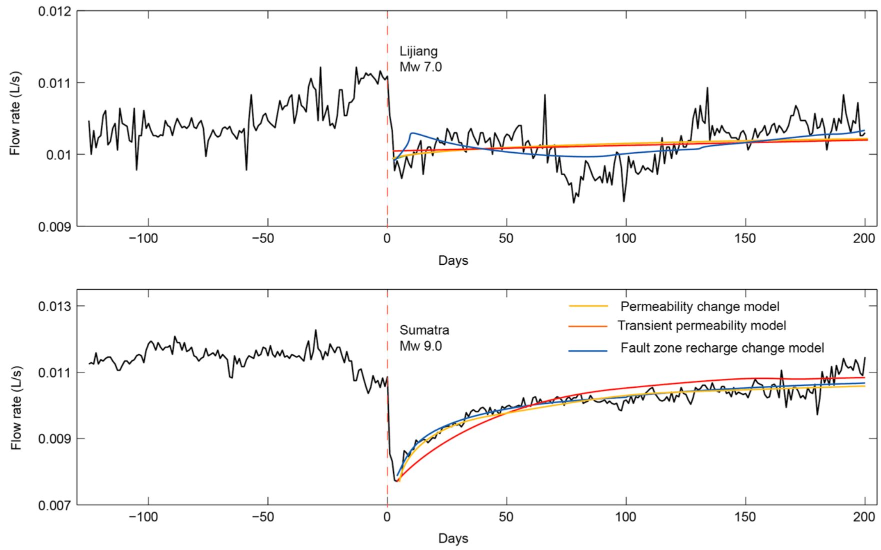

Figure 2. Coseismic spring discharge changes in response to the 1996 Lijiang and the 2004 Sumatra earthquakes. The black curve is the observed data, while the other three curves are modeled flow rate changes using the three different permeability models.

with fractures, we do not favor the first two mechanisms. Instead, earthquake-induced permeability change is more likely responsible for the coseismic changes in discharge.

Currently, there are two different approaches that can be used to explain the coseismic hydrological changes described above (Wang et al., 2017). One is called the permeability change model, which attributes the coseismic change in discharge to sustained or transient permeability changes in the fault zone (Manga & Rowland, 2009). The other is the fault zone recharge change model, which keeps the permeability of the fault zone unchanged. The discharge changes are instead attributed to changes in the hydraulic head that result from changes in permeability perpendicular to the fault zone (Wang et al., 2004) or are caused by a decrease in the pressure gradient due to permeability changes in other locations resulting reduced water recharge into the fault zone.

In the sustained permeability model, the variation in hydraulic head in the fault zone can be described by the groundwater flow equation with an additional term that accounts for recharge to the fault zone (Manga & Rowland, 2009; Zhang et al., 2017):

$$Ss\frac{\partial h}{\partial t} = Kv\frac{\partial^2 h}{\partial x^2} + \frac{Kh}{wD}(h0 - h) \tag{1}$$

with boundary condition

$$h = h0 \quad at \quad x = D, \quad \partial h/\partial z = 0 \quad at \quad z = L, \tag{2}$$

where w is the width and L is the depth of the fault zone, K_v is the vertical hydraulic conductivity of the fault zone, and K_h is the horizontal conductivity perpendicular to the fault zone; S_s is the specific storage of the fault zone. The horizontal aquifer extends to a distance $x = D$ where the hydraulic head is fixed at h_0. The last term in equation (1) is a first-order approximation of recharge. In this model we assume that the storage properties, S_s, do not change. The model can be described by the following four parameters (see Text S1 for details):

$$a = \frac{KvfAh0}{L}; \quad R = \frac{Kvf}{Kvi}; \quad v = \frac{Kh}{DwSs}; \quad T = \sqrt{\frac{vL^2Ss}{Kvf}}, \tag{3}$$

the A in the term a is the cross-section area that fluid is being discharged. We assume that K_v decreases by an amount linearly proportional to the decrease in discharge according to Darcy's equation (Manga & Rowland, 2009).

In the transient permeability model, the hydraulic conductivity of the fault zone changes from the preearthquake permeability (K_{vi}) to the postearthquake permeability (K_{vf}) (Figure 3b), and K_{vf} decreases

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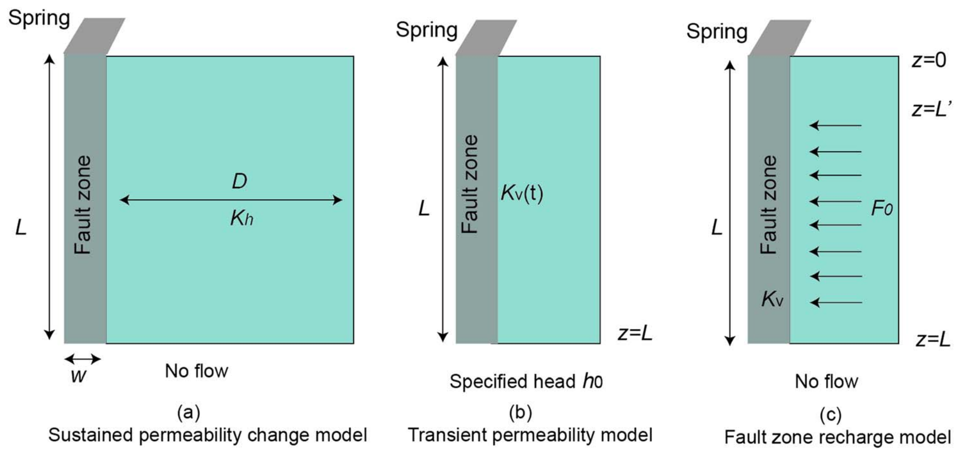

Figure 3. Schematic illustration of conceptual models (according to Manga & Rowland, 2009). (a) Sustained permeability changes in the fault zone. (b). Transient permeability model in which fault zone decrease coseismically and then increases. (c). Fault zone recharge model in which an influx of fluid F_0 causes the head in the fault zone to decrease and hence discharge to decrease.

exponentially with the decay constant λ. The hydraulic conductivity of the fault zone can be expressed as follows (Zhang et al., 2017):

$$K_v(t) = K_{vi} + (K_{vf} - K_{vi})e^{-\lambda t}. \tag{4}$$

K_v is the hydraulic conductivity of the fault zone and the subscripts "i" and "f" indicate values before (initial) and after (final) the earthquake, respectively. Using the boundary condition $h = h_0$ at $z = L$, the groundwater flow equation can be described as (Manga & Rowland, 2009)

$$Ss\frac{\partial h}{\partial t} = \left[Kvi + (Kvf - Kvi)e^{-\lambda t}\right]\frac{\partial^2 h}{\partial x^2} + \frac{Kh}{wD}(h0 - h). \tag{5}$$

The model can be described by the following parameters:

$$Q_0 = \frac{KviAh_0}{l}; \quad R = \frac{Kvf}{Kvi}; \; \lambda; \tag{6}$$

Q_0 is measured and R is known from the magnitude of the changes in discharge rate; thus, only one parameter is needed to fit.

The fault zone recharge change model can be described by a simplified one-dimensional groundwater flow model as follow (Figure 3c) (Manga & Rowland, 2009):

$$S_s\frac{\partial h}{\partial t} = Kv\frac{\partial^2 h}{\partial z^2} + U, \tag{7}$$

where U is the recharge rate to the fault zone per unit volume. At the time of the earthquake we let $U = U_0\delta$ over the depth interval $L' < z < L$, where $\delta = 1$ at $t = 0$ and $\delta = 0$ at for $t > 0$. The solution for discharge is given by (Wang & Manga, 2015)

$$Q(t) = Q_0 + \frac{2KvAU_0}{S_sL}\sum_{n=1}^{\infty}(-1)^{n-1}\sin\left[\frac{(2n-1)^2\pi^2(L-L')}{2L}\right]\exp^{-(2n-1)^2\pi^2Kvt/4S_sL^2}, \tag{8}$$

where Q is the coseismic discharge variation of groundwater, L *is* the length of the aquifer, L' *is* the length of the recharged section of the aquifer, t *is* the time since the earthquake, D *(K/S_s)* is the hydraulic diffusivity of the aquifer, K *is* the hydraulic conductivity, and S_s *is* the specific storage. In the solution to the groundwater flow equation these parameters appear in four other parameters:

$$Q_0, \quad \beta = \frac{2KvAU_0}{S_sL}, \; \Lambda = \frac{2Kv}{S_sL^2}, \; (L-L')/L. \tag{9}$$

Table 1
Model Parameters for Three Different Models

Model name	Parameter					
Model 1 Sustained permeability change model	Earthquake	α	R^{a}	V	T	Misfit (L/s)
	1996 Lijiang	0.011 ± 0.002	0.95	0.002 ± 0.002	1.139 ± 0.006	0.00027
	2004 Sumatra	0.0071 ± 0.0003	0.71	0.007 ± 0.001	2.719 ± 0.168	0.0002
Model 2 Transient permeability model	Earthquake	Q_0^{a}	R^{a}	λ	Misfit(*L/s*)	
	1996 Lijiang	0.0111	0.95	0.0008 ± 0.0001	0.00027	
	2004 Sumatra	0.0109	0.71	0.0207 ± 0.0006	0.0004	
Model 3 Hydraulic head changes model	Earthquake	Q_0	β	Λ	$(L-L')/L$	Misfit (L/s)
	1996 Lijiang	0.0111	−0.0016 ± 0.0005	0.0016 ± 0.0003	0.30 ± 0.09	0.00025
	2004 Sumatra	0.0109	−0.0018 ± 0.00006	0.004 ± 0.00023	0.25 ± 0.00001	0.00023

[a]Fix to this value, the misfit between the best fit model and data is characterized using the root mean squared deviation: $E = \left[\frac{1}{N}\sum_{i=1}^{N}\left(Q_{\mathrm{measured}} - Q_{\mathrm{model}}\right)^2\right]^{1/2}$

Q_0 is the discharge before the earthquake: the other three parameters can be determined by fitting the equation to the time history of the observed spring discharge. Here we use the nonlinear least squares Marquardt-Levenberg algorithm to fit the three models to the observed data (see Text S1 for more details; Manga & Rowland, 2009). We only fit the recovery process of the response as the initial abrupt change process, indicating that the process of decreasing hydraulic conductivity is not complete for the two permeability change models. The calculated parameters with uncertainties and the misfits are listed in Table 1.

Figure 2 compares the observed changes in spring discharge with the modeled discharge for the three models. The fitted parameters are listed in Table 1 with uncertainties. From Table 1, we find that all the models can simulate well the observational data. The fault zone recharge change model and sustained permeability change model simulate the changes in spring discharge following the Sumatra earthquake better than the transient permeability model. Thus, we consider these two models to be better at describing earthquake-induced changes in discharge. For the sustained permeability change model, we find that the ratio of the permeability in the fault zone before and after the earthquake is 0.95 for the 1996 Lijiang earthquake and 0.71 for the 2004 Sumatra earthquake, which means that the fault zone permeability decreased after the two large earthquakes. For the fault zone recharge change model, we find that the recharge term (β) following the two earthquakes is negative for both earthquakes. Since the observed discharge decreased, we may infer that the negative recharge indicates that the fault zone system received less recharge when compared with the recharge before the earthquakes.

Based on the analyses above, we find that either permeability decrease or reduced recharge in the fault zone following the two earthquakes may explain the coseismic decrease in discharge. Further analysis is needed to identify the mechanism. As we described above, the fault zone recharge change model assumes that the permeability of the fault zone is unchanged, while the sustained permeability change model assumes that the permeability of the fault zone changes. Thus, we may identify the coseismic response mechanism by determining whether the permeability of the fault zone changed or not following the earthquake. The baseflow recession analysis proposed by Manga (2003) is chosen for this purpose (Text S2). According to Manga et al. (2003), unchanged baseflow recession (*aD*) after an earthquake indicates that the hydraulic conductivity is unchanged (Zhang et al., 2017). For the Balazhang #1 spring, the recession constant (*aD*) changed from 0.0004 to 0.0002 day^{-1} following the 1996 Lijiang earthquake and changed from −0.0003 to 0.0005 day^{-1} following the 2004 Sumatra earthquake (Figures S3 and S4), which indicates changes in fault zone permeability. Thus, we prefer the permeability decrease mechanism to explain the coseismic changes in spring discharge. However, the permeability model cannot reveal the source of water: the decrease in discharge may result from a decrease in recharge from either shallow cold water or deep hot water. To identify the origin of the water affecting the decrease in discharge, we further constrain the coseismic mechanism using spring temperature data. The temperature in the Balazhang spring decreased following both the 1996 Lijiang earthquake and the 2004 Sumatra earthquake (Figure 4). The temperature decreased from 86.2 °C to 84.1 °C during the 1996 Lijiang earthquake and from 87.6 °C to 83.5 °C during the 2004

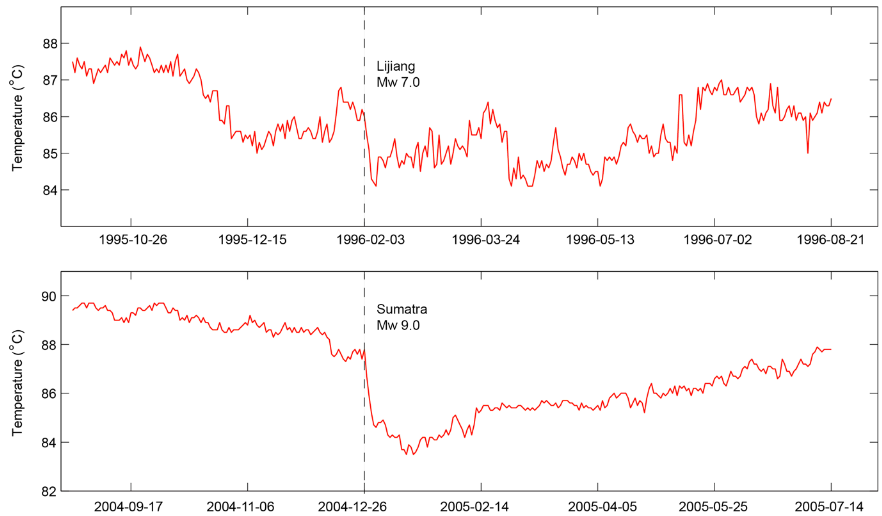

Figure 4. Coseismic temperature changes following the 1996 Mw 7.0 Lijiang and the 2004 Mw 9.0 Sumatra earthquake.

Sumatra earthquake. Thus, the temperature changes are consistent with the coseismic change in discharge. According to geochemical studies, the Balazhang hydrothermal system is characterized by a mixture of deep hot water and shallow cold water (Guo et al., 2017) with a mixing ratio of approximately 3/7 determined by the silica-enthalpy model. A more detailed discussion of this methodology can be found in Text S2 (Fournier, 1977; Powell & Cumming, 2010). The reservoir temperature determined using the Na-K-Mg geothemometer is approximately 220 °C (see Figure S1 in the supporting information). Since both the discharge and temperature of Balazhang #1 spring decrease, an increase in cold/hot water recharge is not possible. One possible reason for the coseismic temperature decrease is that the mixing ratio (cold water)/(hot water) has increased. Considering the decrease in discharge, we may deduce that the decrease in hot water recharge from depth is the process that leads to the decrease in discharge and temperature. Assuming that the changes in spring discharge are induced by changes in recharge from hot water at depth, and that the amount of recharge from shallow cold water is kept unchanged, then the overall change in spring temperature changes is controlled by deep hot water recharge. According to the conservation of energy, the mixed temperature of the spring can be described as follows:

$$m.T = \mu.m.T_r + \ (1-\mu).m.Tc \tag{10}$$

here m is the mass of the spring system after the mixing of deep hot water and shallow cold water; μ is the mixing ratio of hot water. T is the mixed temperature, T_r is the temperature of the deep hot water, and T_c is the temperature of the shallow water. Equation (1) can be rewritten as

$$\mu = (T - T_c)/(T_r - T_c). \tag{11}$$

Since we assume that the changes in spring discharge are caused by changes in recharge from deep hot water, and that recharge from shallow cold water remains unchanged, the amount of deep hot water at time (n + 1) can be described by the following equation:

$$\mu_{n+1}.q_{n+1} = \mu_n.q_n - \left(q_n - q_{n+1}\right), \tag{12}$$

where q_{n+1} is the spring discharge at time n + 1 and q_n is the spring discharge at time n; μ_{n+1} is the mixing ratio at time n + 1, and μ_n is the mixing ratio at time n. The above equation can be simplified to

$$q_{n+1} = (1 - \mu_n)q_n/\left(1 - \mu_{n+1}\right). \tag{13}$$

Combining equation (2) and equation (4), we can obtain the relationship between spring discharge and temperature:

$$q_{n+1} = (T_r - T_n)/(T_r - T_{n+1})q_n. \tag{14}$$

The changes in spring discharge can be modeled by using equation (11); the results show that this simple model can fit the observed data well following both earthquakes (Figure 5). Thus, we argue that the

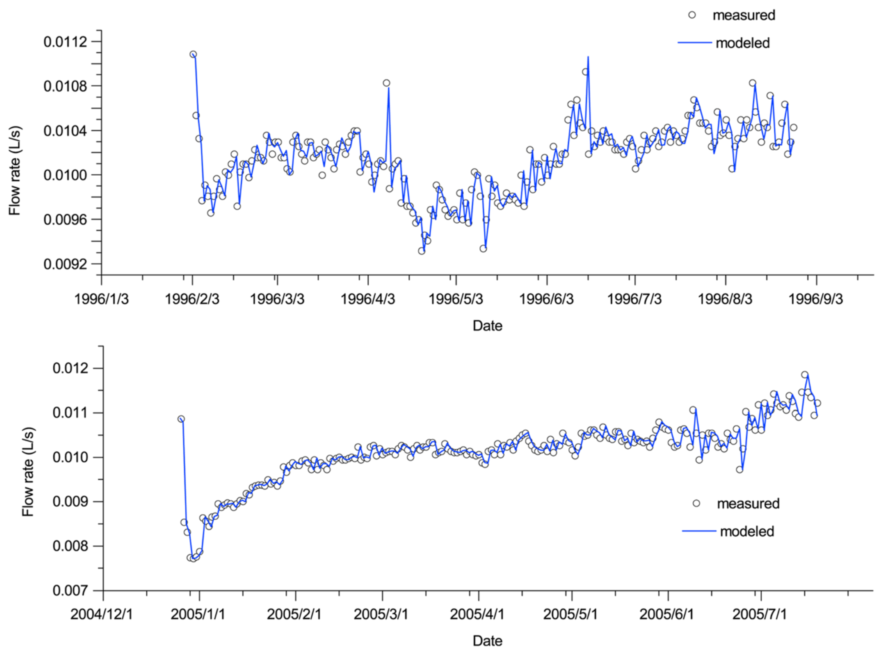

Figure 5. Comparison of the observed flow rate and flow rate modeled using temperature data.

decreased recharge from deep hot water causes the decrease in spring discharge and temperature. Following the 1996 Lijiang earthquake and the 2004 Sumatra earthquake, the decrease in fault zone permeability for the Balazhang #1 spring prevented deep hot water from entering the fault zone and thus led to the decrease in discharge and temperature. Thus, we can conclude that the earthquake-induced clogging of flow paths in the deeper region of the fault zone, which reduced hot water recharge, is the dominant mechanism to explain these coseismic responses. Since the spring system integrates the signal from hydrological processes over large spatial areas, the observed coseismic changes may reflect large scale hydrological changes in the Balazhang geothermal field.

5. Conclusions

In this study, we document the coseismic decrease in hot spring discharge in the Balazhang geothermal field after two large earthquakes. We used three different permeability change models to constrain the mechanism of coseismic discharge decrease. Our results show that decreased permeability in the fault zone produced by seismic waves reduced the recharge to the spring system. Along with the temperature data, we used an end-member mixing model to further identify the mechanism that earthquake-induced clogging of flow paths in the fault zone, which reduces the recharge of deep hot water, may be the mechanism to explain these coseismic responses. The case of earthquake-induced permeability decrease in the geothermal field documented here requires the reassessment of the impact of earthquakes on many engineering applications such as geothermal exploitation, oil well production, underground waste repository safety, and triggered seismicity.

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